Gamma-ray flux variability in the sample of EGRET blazars

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Abstract: We analyze average γ–ray variability statistics for the sample of blazars detected by *CGRO*/EGRET. We re-reduce all the available EGRET observations and analyze light curves by Monte Carlo modeling of the variability statistics including observational artifacts. We show that the observed variability behavior is dominated by the distribution of measurement errors which leads to strong systematical effects in all of the these statistics. General variability behavior detected by us is consistent with non-linear models and shows marginal correlation at long time scales in the structure function. We determine limits on distributions of the variability parameters with synthesis of flare population. We conclude that this method shows that all blazar light curves are consistent with a superposition of multiple flares.

1 Introduction

The EGRET archive provides important opportunity to study variability behavior of the high energy Compton component of γ-ray blazars, which is crucial for multi-wavelength cross-correlation analysis and for further developing of theoretical models (e.g., Urry 1996; Madejski et al. 1996). Although the EGRET archive was investigated extensively (e.g., McLaughlin 1996), the complex nature of the EGRET instrument (Thomson et al. 1993; 1995) together with a complex, non-stationary pattern of blazar variability, makes conclusions uncertain. Effects of relativistic Doppler beaming produce a broad range of time scales and amplitudes which are strongly confused due to limited photon statistics and poor sampling. Relatively short observations also prevent simple auto-correlation analysis. Moreover, statistical behavior of EGRET flux measurements is still far from being understood (e.g., Mattox et al. 1996), and confuses significantly the analysis. In order to understand the real content of physical information, we re-analyze all

publicly available EGRET observations of blazars and model average variability statistics including effects coming from complex distribution of measurement errors. This paper presents preliminary results from our analysis based on a method of flares population synthesis (Magdziarz & Machalski 1993).

2 Data Reduction

The results presented here are based on EGRET data in viewing periods from 0.2 to 428 (1991 April 22 to 1995 September 20). We use all events at E $>$ 100 MeV, and we get positions of sources from EGRET catalogues (Thompson et al. 1995, 1996). The flux is calculated using maximum likelihood method (Mattox et al. 1996) with the LIKE v5.0 software, and Galactic diffuse radiation is described using the model by Hunter et al. (1996). The dominant contribution to the error of flux measurements comes from fitting and subtraction procedure of the composite background model which leads to complex, strongly non-linear flux-error relation and makes the measurement error distributions hard to estimate (Willis 1996).

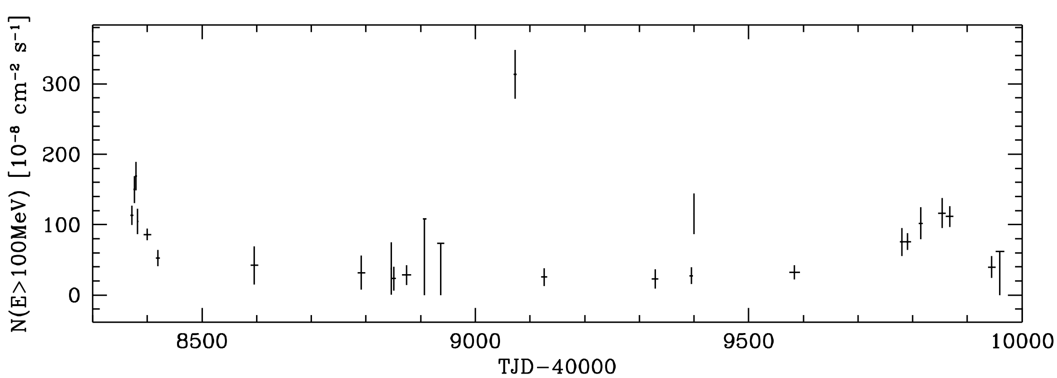

Fig. 1. A light curve from EGRET observations of PKS 0528. Upper limits mark detection below 1σ level, error bars correspond to 95 per cent confidence limit.

Fig. 1 shows an example of a light curve produced from EGRET observations of a bright blazar PKS 0528. Although the baseline of emission seems to be well observed in this particular source, sensitivity of the EGRET detector (Thompson et al. 1993) is relatively low in respect to that necessary for observation of complete light curves in most of the blazar sources. Moreover, strong flaring behavior of the variability makes the light curves dominated by observations near the detection limit. On average about 60 per cent of observational measurements in the EGRET sample of 52 blazars give detection below 1σ limit at the positions of sources known from measurable flux in flaring epochs. The light curves also show also that most of observations do not resolve flaring events in time, since an average of 20 pointings per source is spread over 4 years of observation.

3 Variability Analysis

Assuming a flaring behavior of EGRET blazars light curves, we construct a simple phenomenological model of variability. The flares of radiation are described by amplitude, duration time, and a repetition time lag. The resulting light curve is a superposition of a population of flares (cf. Magdziarz & Machalski 1993). Physics of the source determines some distributions of the above phenomenological parameters which we constrain from the data. In a such treatment, the non-linear behavior of variability produces correlations between the parameter distributions. The instrument sensitivity prevents an analysis of the flare duration, since the data binned in time to a reasonable counts limit cannot resolve flares appearing on time scales $\lesssim 1$ day. This makes the first order structure function degenerate, such that it is constant as characteristic for pure, zero time scale, noise process (cf. Wagner 1996). On the other hand, all blazars in the EGRET sample show in their time history at least some measurement epochs with apparent flux below sensitivity limit of the instrument. This suggests that all of the EGRET measurements detect flare events only, and any quiescent level of blazar emission is under detection limit (cf. Hartman 1996; Willis 1996). Then the distribution of the flux measurements corresponds directly to the distribution of flare amplitudes. We investigate the variability characteristics as an average over the whole sample since the data quality prevents conclusive analysis of the most of individual sources. This treatment is supported by the evidence that the emission mechanism in blazars is related exclusively to the relativistic jet (e.g., Urry & Padovani 1995), and all of the EGRET blazars show significant variability when taking into account selection effects by instrument detection limit (McLaughlin et al. 1996).

3.1 Distribution of Apparent Amplitude

Fig. 2 presents an average distribution of normalized flux measurements in the sample. We normalize a light curve of each source to its average flux, and next calculate by Monte Carlo method the distribution of fluxes including measurement errors. The flux scale is renormalized to the average over the sample. Comparison of the distributions for all of the EGRET measurements (the solid line) and for measurements on the level higher that 1σ (the short-dashed line) shows homogeneity of the sample up to the level of the detection limit. However, the distribution simulated under assumption of constant internal flux of the source (the dashed line) indicates that the overall behavior of the flux distribution is dominated by measurement (i.e., statistical) errors. Deconvolution of the internal flux distribution needs more sophisticated methods since the reduction procedure produces a complex correlation between the measured flux and its error, and the distribution of measurement errors is Gaussian for high level detections only (Willis 1996). The apparent flux distribution shows trace of internal variability up to the flux of $\sim 80 \times 10^{-8}$ photons cm^{-2} s^{-1} where statistical errors begin to dominate. This corresponds to the maximum apparent amplitude of order ~ 7 (in the scale of average flux over the sample) which is, a posteriori, consistent with the non-linear

character of variability (e.g., McHardy 1996). A luminosity function for EGRET sample is poorly determined (cf. Willis 1996 for discussion), and thus the conversion of physical scales is uncertain making the flux distribution smeared out by space distribution of sources.

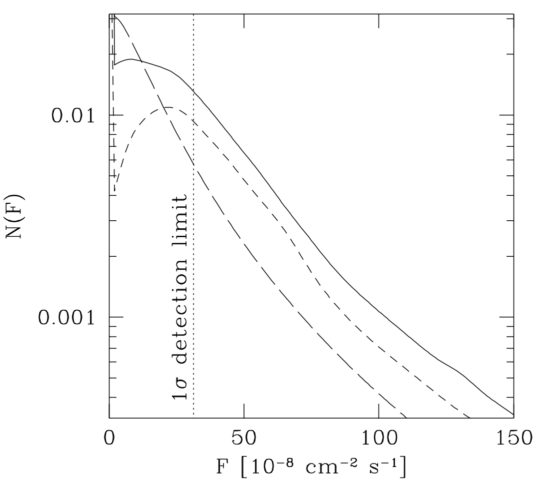

Fig. 2. Distribution of normalized flux measurements averaged over the sample. The solid curve shows the distribution including all of the observations, the short-dashed curve, result for detections better than 1σ, and the long-dashed curve determines the distribution derived without internal variability.

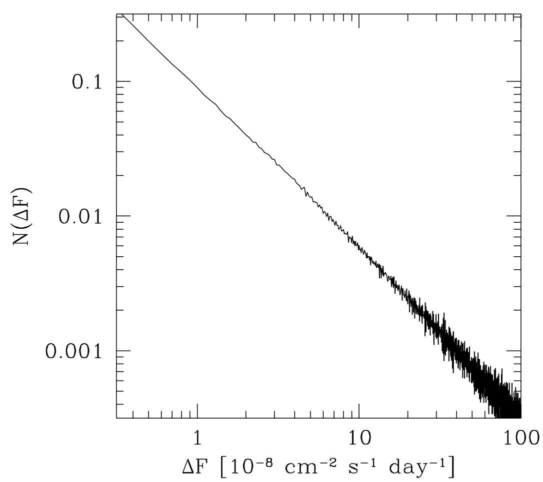

Fig. 3. Distribution of normalized, apparent gradient averaged over the sample of EGRET blazars. The distribution is homogeneous, and well described by a power law functional dependence. The gradient scale is renormalized to the flux average over the sample.

3.2 Distribution of Apparent Gradient

The observed light curves in EGRET sample have in average 20 data points, much less than necessary to study correlation decaying time scales (e.g., Sugihara & May 1990). However, some information may be still retrieved from an average distribution of flux temporal gradients which corresponds to a distribution of the first derivative of the observed light curve. Fig. 3 presents the average gradient distribution over the sample calculated using the Monte Carlo method and including measurement errors. The gradient scale is defined in respect to the average flux, just as for the amplitude distribution. The distribution indicates no internal structure and shows pure power-law functional dependence. The steep index of the distribution indicates that small flares are much more frequent than strong ones. However, despite of complex structure of light curves, the variability process appears to be homogeneous up to the Nyquist frequency limit of ~ 0.07 day^{-1} defined by sampling. This is generally consistent with the light curve produced by superposition of identical flares of radiation with no indication for any duty cycles. The average variability gradient estimated from the sample is $\sim 10^{-6}$ pho-

tons cm^{-2} s^{-1} day^{-1}, however, since the light curves are undersampled in time, this may be treated as an upper limit only.

3.3 First Order Structure Function

We calculated an average structure function over the sample by normalizing the light curve of each source to its dispersion. This normalizes the structure function at its asymptotic long time scale range and preserves information on autocorrelation function over the averaging procedure, assuming that the process is stationary. The dispersion is reasonably approximated for the EGRET data since the light curves undersample the variability time scales. On the other hand, an undersampled light curve of pure stochastic stationary process should give flat structure function (Rutman 1978) which was indeed found in some EGRET data (e.g., Wagner 1996; von Montigny & Wagner 1996). The average structure function we derived (Fig. 4) fails the standard behavior, and indicates clearly internal correlations on time scales longer than $\sim$ 1200 days.

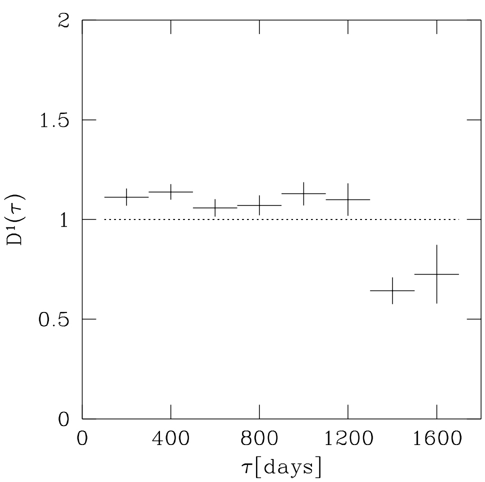

Fig. 4. The average first order structure function in the sample of EGRET blazars. The time process is normalized to its average dispersion. Vertical error bars indicate 95 per cent confidence limit.

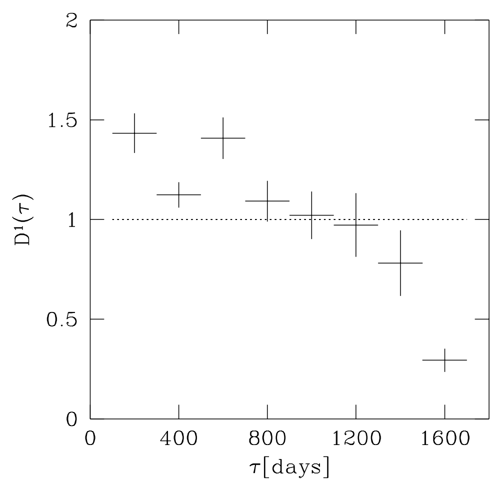

Fig. 5. The average structure function of measurement errors, calculated under assumption that the internal flux of each source is constant (normalization is the same as on Fig. 4).

The structure function is additive with any uncorrelated short time scale noise, well representing measurement errors (Simonetti et al. 1985). This allows the determination of the basic level of observational artifacts affecting the structure function. Fig. 5 presents the average structure function calculated over the observations of EGRET sample, but under assumption of constant internal source flux. The function, however, shows similar basic level and similar behavior as that calculated for the measurement flux. This indicates that the time process is dominated by measurement errors or by the nature of the sampling, and the flux measurements are indeed strongly correlated with their errors.

4 Conclusions

Our preliminary analysis shows that the variability pattern in the EGRET sample of blazars is strongly affected by measurement errors, and correct understanding of the flux measurement statistics is crucial for understanding physical content of the EGRET data. The variability shows generally uniform pattern with power law distribution of temporal flux changes. All of the statistics are consistent with non-linear models of variability which may produce, contrary to the linear ones, flaring light curves with saturation of time scales (e.g., Vio et al. 1992). There is a little evidence in the structure function for suppressing the long time scales which may be manifestation of reduced flaring probability near large flares. This behavior is well described by self-organizing critically models, and seems to be universal in accreting systems (Leighly & O'Brien 1997).

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